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FINAL REPORT

VELA NETWORK EVALUATION AND AUTOMATIC PROCESSING RESEARCH

TEXAS INSTRUMENTS INCORPORATED
Equipment Group
Post Office Box 6015
Dallas, Texas 75222

Prepared for

AIR FORCE TECHNICAL APPLICATIONS CENTER
Alexandria, Virginia 22314

Sponsored by

ADVANCED RESEARCH PROJECTS AGENCY
Nuclear Monitoring Research Office
ARPA Program Code No. 5F10
ARPA Order No. 2551

31 July 1975

Acknowledgment: This research was supported by the Advanced Research Projects Agency, Nuclear Monitoring Research Office, under Project VELA-UNIFORM, and accomplished under the technical direction of the Air Force Technical Applications Center under Contract Number F08606-75-C-0029.

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- A preliminary evaluation of the Korean Seismic Research Station;

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19. continued

Short-Period Spectral Discriminants
Maximum Entropy Spectrum
Phase Energy Ratio
KSRS Short-Period Array Evaluation
Automatic Signal Detectors
Array Processing
Arrival Times
Spectral Analysis Package
Complex Cepstrum

20. continued

- The development of an optimum automatic seismic detector;
- The investigation of adaptive beamforming techniques and distributed signal models as applied to interfering seismic events;
- The development of a network magnitude bias model, and the investigation of various short-period seismic discriminants; AND
- The development and evaluation of an interactive graphics system for the PDP-15 computer to process seismic data, including data from the Seismic Research Observatories.

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- The development of an optimum automatic seismic detector
- The investigation of adaptive beamforming techniques and distributed signal models as applied to interfering seismic events
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- The development and evaluation of an interactive graphics system for the PDP-15 computer to process seismic data, including data from the Seismic Research Observatories.

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SECTION I
INTRODUCTION

This final report summarizes work performed under Contract Number F08606-75-C-0029, entitled VELA Network Evaluation and Automatic Processing Research, by Texas Instruments Incorporated at the Seismic Data Analysis Center (SDAC) in Alexandria, Virginia. The program, which was conducted during the period from 1 December 1974 to 31 July 1975, consisted of the following five tasks:

- Preliminary investigation of the noise and signal characteristics at the Korean Seismic Research Station (KSRS)
- Development of a practical operational detector for seismic events
- Evaluation of adaptive beamforming techniques for separating interfering events, and development of distributed signal models for use with adaptive beamforming filters
- Development of a seismic network magnitude bias model which takes non-detecting stations into account, and the investigation of various short-period discriminants
- Continued development and evaluation of an interactive graphics system for the PDP-15 computer to process seismic data, including data from the Seismic Research Observatories.

The detailed results obtained for these tasks have been presented in a series of nine technical reports. This final report summarizes their results in Sections II through VI. References are given in Section VII, and a list of all reports issued under this contract is in the Appendix.

SECTION II

EVALUATION TASK

The results of the evaluation task are presented in Technical Report No. 5 on the Korean Seismic Research Station (KSRS). No report was written on the evaluation of the Seismic Research Observatories (SRO) since no data from these station were available during the contract period. However, software for this purpose was developed as part of the System Engineering Task, and will be described in Section VI.

Technical Report No. 5: Evaluation of the Korean Short Period Array

This study was similar in purpose and scope to that performed by Texas Instruments Incorporated at NORSAR (Ringdal and Whitelaw, 1973); results are summarized below.

The Korean Seismic Research Station (KSRS) had useable data for only 36 teleseismic events from a data base of 123 Eurasian events recorded during 29 April 1973 to 26 July 1973 and November 1974. Eight seismic events, five from the Caspian Sea-Greece-Turkey region and three from the Kamchatka region, had signal-to-noise ratio (SNR) greater than 5.0 dB and were used in the signal analyses. Six noise samples from November 1974 were analyzed for this report. Data quality of the useable signal and noise samples was very good. Sensors 6, 7, 10, 16, and 17 were responsible for the majority of the data losses; however, on the average, 17 sensors were operational. There were essentially no spikes or clipped peaks in the data.

Major results and conclusions are:

1. Data Base

- The November data was significantly superior in quality to the data from 29 April 1973 to 26 July 1973.

2. Noise Analysis

- The noise spectra were very simple with major peaks in the 6-second microseismic band and rapidly decreasing amplitudes at shorter periods. A minor peak (30 dB lower than the peak at 0.16 Hz) occurred at 3.2 Hz; this peak was not found in the NORSAR noise spectra. No significant temporal or spatial variations in the noise spectra were observed.

- The average RMS noise amplitude of unfiltered single-sensor data was 10.9 mμ and that of standard-filtered infinite-velocity beam data 0.35 mμ. These values are approximately three times higher than the corresponding amplitudes at NORSAR.

- Multiple coherence levels were relatively low at all frequencies above 0.5 Hz.

- Frequency-wavenumber spectral analysis suggested that noise energy below 1 Hz was caused by Rayleigh-mode surface waves from the southwest and northeast while noise energy above 1 Hz was random.

- Noise reduction achieved by beamforming was slightly higher than theoretical random noise reduction due to the suppression of the dominant propagating surface wave energy at low frequencies.

3. Signal Analysis

- Signal similarity, observed visually and calculated by crosscorrelation techniques, was quite good for the Caspian Sea-Greece-Turkey events. The Kamchatka events generally had poor signal similarity.

- Signal amplitude variations between sensors were relatively small with an average variation of 1.3 dB.

- Time delay anomalies were consistent and nearly zero for the Caspian Sea-Greece-Turkey events. The Kamchatka events had inconsistent and invalid delay anomalies caused by low SNR's.

- Eurasian signals usually had similar spectral shapes and substantial amounts of high frequency energy. In general, KSRS spectra were very similar to spectra measured at NORSAR. The limited ensemble of events prevented any determination of regional dependence.

- The frequency-wavenumber spectral analysis were consistent with propagation near the great-circle azimuth at velocities near those predicted by the Jeffrey-Bullen tables.

- Array beamforming signal degradation for all events averaged 1.6 dB for the filtered plane wave beam. The average degradation for the adjusted-delay beam was 1.3 dB for the events having consistent delay anomalies. Signal degradation was less for events having higher SNR's.

- The filtered plane-wave beam improvements in SNR averaged 11.8 dB for all events and had no significant regional variations, nor did the filtered adjusted-delay beam

improvements. These values after correction for signal degradation were almost equal to the theoretical SNR improvement, 10 log (number of sensors), or 12.3 dB. In general, no significant SNR improvements were obtained by adjusted-delay and diversity-stack beamforming.

- KSRS m_b's averaged about 0.3 magnitude units less than LASA and NOAA m_b's. This negative bias may be attributable to atypical local geologic structures or to incorrect B values.

- For detection of Eurasian events, a bandpass filter with approximate corner frequencies at 1.0 and 2.5 Hz and a very sharp roll off at low frequencies appears to be optimum.

4. KSRS Detection Threshold

- A maximum likelihood procedure was used to estimate the KSRS detection threshold from a data base of 36 teleseismic events. The 50 percent threshold estimate was 4.4 magnitude units while the 90 percent threshold estimate was $m_b = 4.5$. Due to the small sample size these results are probably unreliable.

SECTION III

DETECTION METHODS

The detection methods task under this contract consisted of the development of a practical automatic seismic event detection algorithm. The results of that study were presented in Technical Report No. 7.

Technical Report No. 7: An Automatic Seismic Detection Algorithm

Fisher and conventional power automatic seismic event detectors utilizing automatic threshold adjustment were designed and evaluated on Korean short-period array data. Detector performance was evaluated both with and without a non-casual quality control algorithm and a prefilter. Performance at different detector integration times and at different alarm rates was also investigated, and the ability of the detector to correctly pick arrival times and signal azimuth was evaluated. A simple frequency-wavenumber detector was designed and implemented, and the feasibility of installing the best detector design on the Korean station controller was investigated.

All detectors investigated used a beam velocity of 15.1 km/sec and azimuths spaced at 30° intervals over the region of interest, plus another beam directed toward the southwestern Pacific Ocean. Prefilters, when applied, passed energy at frequencies between 0.5 Hz and 3.2 Hz. Integration times of 0.8 and 3.2 seconds were investigated.

The automatic threshold algorithm set the detection threshold at the level where a pre-specified number of alarms occurred, when behavior over a sufficiently long time interval was considered. Tests on noise samples showed that the algorithm performed satisfactorily.

Data covering one hundred seventy-two events reported by the Preliminary Determination of Epicenters (PDE) list were processed with each detector configuration, using quality control and filtering, and fixing alarm rates at 15, 10, 5, and 2 detections per hour. Ninety-seven events were also processed without quality controls or filtering. Claimed detections were required to occur within 15 seconds of the arrival time predicted on the basis of standard travel times. A histogram of detection probability as a function of magnitude was developed from the results, and fit by a maximum likelihood procedure (Ringdal, 1974) to a function derived by assuming that the detection probability was a cumulative Gaussian function of magnitude. The magnitude at which 50% of the events were detected, as determined from this detection curve, was taken as the criterion of detector performance.

It was found that detector type and integration time had little effect on detector performance at a fixed alarm rate. Detector performance was uniformly degraded by about 0.6 magnitude units when quality controls and the prefilter were omitted. Therefore, all further results presented here refer to detectors employing quality controls and prefiltering.

A great fraction of the events were detected on a beam from some other azimuth than the great circle path to the event epicenter. If detections were not constrained to appear on the correct azimuth, the 50% threshold was about magnitude 4.8, with variations of about 0.1 magnitude units for various detector designs. If detections were required to appear on the correct azimuth, the 50% threshold increased to about 5.1, with very little variation between the different designs. On a subset of this data sample an analyst found the 50% detection threshold to be magnitude 4.4.

The cause of this degradation was the small aperture of the Korean short-period array, which resulted in beams whose patterns were greatly overlapping. Noise in the integration gate had the effect of distorting the first signal motion enough to produce nearly the same amplitude

on a number of neighboring beams. Since timing information alone is used to locate seismic events, the Korean array performance may be satisfactory without azimuthal constraints.

The arrival times picked by the automatic detectors were compared with those found by an analyst for a small sample of events. It was found that the detector-picked arrival times were generally later than those picked by the analyst. The timing errors were less for the detectors with longer integration times, but the average error never exceeded 3.0 seconds for any detector. The standard deviation of these timing errors, which is a more important parameter than their absolute value if it is desired to minimize them, was also less for detectors with longer gates, and did not exceed 2.5 seconds in any case.

A simple frequency-wavenumber detector was implemented for each detector design by forming beams with velocities of 15 km/sec and 10 km/sec, each narrowband filtered at 1.0 Hz and 1.8 Hz. Approximately 30 events were processed with these detectors, and it was found that the 15 km/sec beam and 1.0 Hz prefilter consistently gave the best performance. Consequently it is assumed that a frequency wavenumber detector probably offers no advantage over a wideband detector. Furthermore, these results show that our wideband detector design, which is closest to the successful frequency-wavenumber detector, is near optimum.

Since there is no significant difference in detection capability between the detectors examined here, the choice of the optimum detector can be made on the basis of computer core requirements and execution time. It is estimated that with the aid of the Advanced Array Transform Processor included at KSRS, execution time for the conventional power detector would be about 0.3 of real time, and that core requirements would be about 4.2 thousand words, while more memory would be required for the Fisher detector.

At this rate, about 0.03 seconds are required to process one datum point, when the data are sampled at an interval of 0.1 second. Since the other functions of the station processor require on the order of 0.050 seconds per 0.1 second sample point, the detector implemented here will not interfere with those functions.

In the present station processor design, about five thousand words are typically available for the autcmatic detector. Consequently core requirements will probably not hamper detector performance.

A corrolary of these results is that no trade-oif is required between cost and performance for this detector. Its full performance can be obtained without any additional cost in terms of computer requirements.

SECTION IV

SIGNAL ESTIMATION TASK

The results of this task are presented in three reports. The utility of the adaptive beamforming processor as applied to the interfering event problem is investigated for short-period data in Technical Report No. 2 and for long-period data in Technical Report No. 6. Technical Report No. 3 is concerned with a mathematical study directed toward implementation of Wiener adaptive multichannel filtering with distributed signal models.

A. Technical Report No. 2: Adaptive Beamforming Performance on Korean Short-Period Interfering Events

This report deals with results obtained by applying a maximum likelihood adaptive beamforming processor to events simulated by mixing Korean short-period data. Its purpose was to investigate the value of this technique for detecting the arrival of a second seismic event buried in the coda of a first-arriving event at various signal-to-noise ratios. The algorithm used was essentially identical to that developed by Barnard and O'Brien (1974).

Two data samples, one with an on-azimuth signal and the other containing an interfering event, were summed to form a composite sample from which the adaptive filter sets were designed and applied to the two samples individually. The outputs of the two filters were added to form the composite beam used in simulating the actual situations encountered in practice. Amplitude-rise measurements were made by taking the ratio of the composite-trace maximum peak-to-peak amplitude after the signal arrival to the corresponding amplitude before the signal arrival. The experimentally determined

detection threshold was that power separation between the events, at an average single sensor, where a 6 dB amplitude rise was achieved.

The results varied from case to case and are summarized in the following points:

- In the first mixed-event simulation, where the interfering event had poor waveform similarity and time-varying relative amplitudes across the array, a 0.2 m_b detection threshold reduction with respect to the beamsteer threshold was obtained by adaptive beamforming. The second simulation used the same on-azimuth signal as in the first and employed an off-azimuth interfering event with better waveform similarity. The threshold reduction was slightly more than in the first simulation. However, with a 7-point-long adaptive filter and 90^o azimuthal separation between the two events, adaptive beamforming was able to reduce the detection threshold by 0.5 m_b units from the beamsteer threshold. Using the 7-site inner-ring array, a detection threshold reduction of about 0.3 magnitude units relative to beamsteering was achieved in the third mixed-event simulation. In this case, the adaptive gain can be attributed to the poor time-shift-and-sum beam pattern. With the 19-site full array in this same simulation, and adaptive-processing results are comparable to those of beamsteering because mutual cancellation between on- and off-azimuth signals occurred at high convergence rates.

- The beamsteer array gain relative to the single-sensor level was more affected by addition or subtraction of interfering-event energy than that of adaptive beamforming. As the event-separation increased, the ABF gain relative to beamsteering tended to increase. For on-azimuth signal magnitude estimates,

the adaptive-beamforming processor seemed to produce more accurate results than beamsteering.

- Among the various prefilters used, the 1-Hz-wide passband yielded the best results. The adaptive gain for various passbands was comparable as long as signal similarity did not vary significantly among the passbands. After the arrival of the on-azimuth signal, adaptive beamforming tended to suppress the off-azimuth interfering event less with wider passbands.

- In these bodywave simulations, both the beamsteer and adaptive processors did not perform as well as in the long-period mixed-event simulation using ALPA data, particularly in the case of the adaptive processor, because signal similarity for the short-period P-wave signals from the spring 1973 Korean data was not as good as for the Rayleigh waves processed in the long-period study.

In the spring of 1973, the Korean short-period array data appeared to have some digitizer problems. Whether these problems have significant effects on the results presented in this report is still not known. The digitizer problems seem to have been corrected in the November 1974 data. On the basis of a limited number of samples, the data quality during this period seems to have been greatly improved and seems to have better signal similarity across the array. Repeating this work with the November 1974 data might produce significantly better detection results.

B. Technical Report No. 6: Adaptive Beamforming Performance on Alaskan Long-Period Array Interfering Events

This report presents the results obtained from applying a time-domain maximum likelihood adaptive-beamforming processor to simulated

mixed-event data from the Alaskan Long-Period Array. The experimental procedure was similar to that reported in Technical Report No. 2 above. Adaptive-beamforming detection threshold reduction with respect to the beamsteer threshold was investigated as two parameters were varied: the time separation between Rayleigh wave arrivals, and the azimuthal separation between the events.

Two sets of simulations were performed in this study. First, two events with azimuths differing by 180° were overlapped. The detection threshold for the beamsteer and ABF processor, found in the same way as in the short-period study, was measured as a function of the difference between the arrival times of the events at the reference sensor for values of this difference between 0 and 7 minutes. Although the threshold of each detector varied by as much as 5 dB, the difference between thresholds, or the threshold reduction, was relatively constant at 11 dB. This result was due to the fact that neither set of filter weights changed appreciably from one time separation to another. Consequently, fortuitous addition and cancellation of the cycles contributing to the peak motion caused these peaks to rise and fall by the same amount for each processor as the time separation was varied.

To show that the ABF's filter weights remained relatively constant, its response pattern was calculated at periods near that of the dominant energy. Nulls as deep as -30 dB were found near, but not at, the azimuths of the interfering event. Examination of frequency-wavenumber spectra for the interfering event confirmed that the nulls were at the azimuths of energy multipathed away from the great-circle path. Consequently it was concluded that the ABF was performing directional filtering as well as taking advantage of short-term correlations in the signal.

In light of these results, the study of the threshold reduction as a function of azimuthal separation was conducted at a fixed time separation.

Here it was found that the ABF detection threshold increased smoothly and rapidly to 30 dB at an azimuthal separation of 120°, and remained there for larger separations. By contrast, the beamsteer threshold never was more than 14 dB, and varied substantially with azimuthal separation. Consequently the ABF achieved a threshold reduction of 24 dB at some separations.

The experimental work presented in this study is limited, but nevertheless supports a consistent picture of the ABF's performance relative to the beamsteer. The ABF is indeed performing directional filtering, at least in part, as shown by the correspondance of its response pattern nulls with peaks in the f-k spectra at various times and frequencies. The ABF's superiority, at any azimuthal or time separation, is due to two factors. First, its response pattern nulls are deeper than the beamsteer's deepest nulls in most cases, especially for energy at periods greater than 25 seconds. Second, it is able to place these nulls at the interfering event azimuth, rather than in a direction determined by the array geometry as in the case of beamsteering. The first of these advantages is due to the ABF's large number of degrees of freedom, and the second is due to its adaptive nature.

Quantitatively, the conclusions are on a less firm footing. The arguments above and the experimental results suggest that the ABF threshold suppression is not a function of time separation for a wide class of event pairs, but the numerical value of that reduction depends on several factors and consequently is not predictable in general. The azimuthal dependence of the reduction is neither constant nor predictable, for the same reason. However, the reduction was as high as 24 dB (1.2 magnitude units) and was at least 9 dB (0.45 magnitude units) better for the ABF than for the beamsteer at all time separations and at all azimuthal separations greater than 45°.

Finally, it is important to reiterate that the ABF processor has shown the capability to recover on-azimuth signals up to 30 dB below the interfering signal (1.5 magnitude units) for some cases; this capability is 12 dB

better (0.6 magnitude units) than any other technique that has been tested. Thus, the ABF has the potential to significantly reduce the interfering event problem provided that a surveillance network includes long-period arrays.

C. Technical Report No. 3: Time Domain Wiener Adaptive Beamforming With Distributed Signal Models

Among the problems encountered with the maximum likelihood adaptive multichannel filters presented in the previous two reports are mutual cancellation of interfering events, signal distortion, and sensitivity to slight deviations from an ideal plane wave signal model. The present report deals with two algorithms for implementing Wiener adaptive filtering with distributed signal models, which may prove useful in eliminating or ameliorating these problems.

Each algorithm discussed requires some method for estimating the crosscorrelation functions between the signal and the channels entering the adaptive beamformer. These crosscorrelation functions are estimated by convolving the time-lag probability density function $p(\tau)$ corresponding to a specified velocity-azimuth incoming-energy distribution with the signal autocorrelation function, which is approximated by averaging the input-channel autocorrelation functions.

Estimating the time-lag probability density function $p(\tau)$ for various directionally-distributed signal models is an interesting problem in its own right. In this report three basic models are described. The first is an inverse velocity space model, in which the signal-model probability distributions are specified as a function of the two-dimensional inverse velocity vector $\vec{\mu} = \vec{V} / (\vec{V} \cdot \vec{V})$, where $\vec{V}$ is the incoming energy's apparent velocity in the plane of the array. The second is a distributed ring model where all incoming energy is concentrated at a single apparent velocity V with respect

to the plane of the array, but is distributed over a range of azimuths according to a known probability density function $p_\theta(\theta)$. The final model is a velocity azimuth space model, in which the signal model is specified both as a function of the apparent velocity V in the plane of the array and as a function of the arrival azimuth θ.

SECTION V
DISCRIMINATION TASK

The discrimination task was divided into two areas. The first area, considered a statistical aspect of the discrimination problem, concerned the bias introduced into magnitude estimates made by averaging only detection stations of a long-period network. The nature of this bias was investigated, and means for its reduction were presented. The second area was concerned with short-period discriminants at regional and teleseismic distances. Unfortunately, the experimental problems involved in each of the studies in this area did not allow the establishment of any firm conclusions, and these studies were reported in technical memorandum form only.

A. Technical Report No. 1: Maximum Likelihood Estimation of Seismic Event Magnitude From Network Data

When estimating the magnitude of an earthquake recorded by a seismic network, the common approach is to average all magnitudes measured at those individual stations that actually detect the event. This procedure often leads to overestimating the magnitudes of events that are near the network detection threshold since many stations will not detect such events, and therefore will be ignored in the averaging procedure. Clearly, those stations will usually be the ones with the weakest signal, and the net effect is to introduce a positive bias in the estimation procedure.

Herrin and Tucker (1972) computed the expected error introduced by the above magnitude estimation method for the case of a homogeneous or near-homogeneous network. Their basic assumption was that world-wide

bodywave magnitudes of a given event follow a Gaussian distribution with unknown mean μ and variance σ^2. They called μ the 'true' magnitude of the event, and computed the bias relative to this (unknown) value as a function of σ^2 and the network characteristics.

We further assume that at a given station, an event is detected if the station magnitude exceeds a certain threshold value. This threshold value may be treated as a random variable, if desired, but we will first assume that it is actually measured as the 'noise magnitude' at the expected time of signal arrival. Clearly, it is more satisfactory to know the precise threshold magnitude than a statistical distribution, especially when taking into account that the statistical distribution may not always be valid.

It is assumed that for a given event, records from a network of stations are examined. Further, it is assumed that the threshold magnitudes are known, and that for those stations that detect the event a magnitude is computed. Finally, it is assumed that all station observations may be considered independent. Then the probability that the given set of threshold magnitudes and event magnitudes occurs is calculated as a function of the true event magnitude and its standard deviation, and this likelihood function is maximized with respect to the unknown parameters, yielding an estimate of their value.

In general, a closed-form expression of a maximum likelihood estimator may be difficult or impossible to find. Therefore, the exact statistical distribution of the estimator usually cannot be derived (except with respect to asymptotic properties). In many cases, the most practical way to determine the statistical properties of the estimator is to simulate its performance in selected cases.

Several different simulation experiments were conducted. Typically, the procedure for each of these was as follows:

- Define a hypothetical seismic network with known threshold magnitudes $a_1, \ldots, a_n$ for each of the n individual stations of the network.

- Select an event magnitude μ and standard deviation σ, thereby assuming that the distribution of actual station magnitudes is known.

- Simulate 100 events recorded by this network. For each event, n independent, normally distributed random numbers $x_1, x_2, \ldots, x_n$ are generated from the Gaussian distribution (μ, σ^2). These numbers are assigned as station magnitudes for the particular event.

- In each of the 100 cases, determine detection/no detection for each of the n stations, by comparing x_i and a_i $(i = 1, 2, \ldots, n)$. Then estimate network event magnitude in the conventional way (by averaging over all detections) and by maximizing the likelihood function.

- Compare the resulting 100 conventional and maximum likelihood estimates to the expected theoretical distribution of event magnitudes.

Event magnitudes μ were selected ranging from 3.5 to 5.5. The standard deviation σ of the world-wide magnitude distribution was set at 0.4 magnitude units in all cases. Finally, we applied the maximum likelihood estimation technique both with σ assumed to be known and with unknown σ.

The first group of simulation experiments was carried out in order to determine the performance of the maximum likelihood estimator under ideal circumstances, i.e., when the correct value of the standard deviation σ of the magnitude distribution was known a priori. Thus, the likelihood function in these cases was maximized as a function of one variable μ.

This experiment was performed using both conventional and maximum likelihood estimation techniques. The major results from these simulation experiments are as follows:

- At magnitude 5.5 the two methods are essentially equivalent and unbiased relative to the true magnitude.
- At 5.0 and lower magnitudes, the conventional estimates exhibit a significant positive bias. The size of this bias shows a gradual increase from about 0.1 magnitude unit at 5.0 to about 0.5 units at magnitude 4.0.
- The maximum likelihood estimates are clearly superior to the conventional estimates, and show essentially zero bias down to magnitude 4.0.
- At magnitude 3.5, both methods show less satisfactory performance, mainly due to the low detection probability at this magnitude.

In order to get an impression of what happens when the number of network stations increases, while the average individual station detection capability remains constant, we conducted an experiment with 100 stations. It was found that:

- The maximum likelihood estimates converge to the true magnitude as the number of stations increases.
- The conventional estimates converge to a magnitude value that is significantly biased relative to the true value as the number of stations increases.

Thus, if an existing network is augmented with new stations of about the same detection capability, this will improve the maximum likelihood

magnitude estimate, but not reduce the bias inherent in the conventional estimate.

The likelihood function may be maximized as a joint function of μ and σ provided that the network consists of at least two stations, and that at least one station detected the event. In order to minimize the effects of gross error in the estimate of σ on the resulting estimate of the magnitude μ, we restricted σ to values within a predefined range in the estimation procedures. This range was, somewhat arbitrarily, set to

$$0.25 \leq \sigma \leq 0.60 .$$

From the results of these simulations, the following major points may be made:

- For an event of magnitude 5.5, no significant difference is seen compared to the case of known σ. This is consistent with the observation that the maximum likelihood estimates of μ and σ are independent if all stations detect.

- For $\mu = 5.0$, 4.5, and 4.0, the maximum likelihood estimates are significantly better than the conventional estimates. Furthermore, it appears that the former estimates are only slightly inferior to those made with a known value of σ.

As a final part of the simulation experiment, we investigated the consequence of deliberately using a wrong value of σ when maximizing the likelihood function. The effects of such a mistake will be most pronounced in those cases when few stations detect. The resulting estimates for $\mu = 4.0$, $\sigma = 0.4$ as simulation parameters, with σ set to 0.25 and 0.60, showed a definite bias in both cases, although the maximum likelihood estimates are still more accurate than the conventional estimates.

From this last result we conclude that, unless σ is known with good confidence, the best way in practice to apply the maximum likelihood estimation method is to use a two-parameter maximization technique. and allow σ to vary within predefined, reasonable bounds.

The maximum likelihood technique was applied to actual seismic data recorded by the World-Wide Standard Seismograph Network (WWSSN) and by the Very Long Period Experiment (VLPE) network, and the results compared to conventional estimates. For application to WWSSN data, σ was set to 0.4, and the noise was assumed to have small variability about a mean value. The data used were taken from an earthquake swarm. The maximum likelihood estimates of the event magnitudes corresponded closely with those found independently at NORSAR. Those found by the conventional technique agreed with those found at NORSAR at magnitudes above $m_b = 5.0$, but below this magnitude the conventional estimates saturated at a magnitude near 5.0. Maximum likelihood estimates showed no saturation down to magnitude 4.0.

The same experiment was performed using a data set collected by Lambert (1974), consisting of magnitudes measured by VLPE stations. A signal standard deviation of 0.4 was used, and the variability of the threshold magnitudes was assumed to be 0.4 based on measurements of the noise there. The detection capability of the VLPE network, based on conventional estimates of magnitude, was found to be about 0.2 magnitude units higher than that using the maximum likelihood technique. The estimated frequency-magnitude relationship also depended on the technique used to find the magnitude, with the conventional method yielding a somewhat higher rate of change of event frequency with magnitude than that found using the maximum likelihood estimates.

We recommend that further research be carried out in order to obtain more complete data on the maximum likelihood method and its underlying assumptions. Specifically, the following topics are suggested:

- Further verification of the Gaussian model for world-wide seismic magnitude distribution for a given event; especially for surface wave magnitudes.

- More precise determination of the standard deviation σ in the above distribution, and its possible variation with source function, event depth, magnitude, and seismic region.

- Comparison of σ for array station networks and σ for single station networks.

- Actual application of the maximum likelihood technique to existing and planned networks. For such applications, it is recommended that
  - all threshold values of non-detecting stations should be actually measured for each event detected by the network
  - a narrow, but realistic range of σ should be specified, and the likelihood function should be maximized as a function of the two parameters (μ, σ).

It is strongly recommended that in any future operational network all threshold magnitudes for non-detecting stations should be measured along with the magnitudes of the detecting stations. It is felt that realistic estimates of the magnitudes of small and intermediate events will ultimately have to take all of this information into account, whether or not the techniques and models used in this report are to be applied.

B. Technical Report No. 8 (Memorandum): Corner Frequency Study

The purpose of this study was to examine short-period spectral discriminants, and in particular discriminants based on corner frequency, as this parameter is expected to reflect differences in source dimension. In

order to do this a method of estimation based on the maximum entropy spectrum was developed. This method does away with the conventional assumption that the data are zero outside the sample interval, which is especially unrealistic for low signal-to-noise events. This result is achieved by estimating the autocorrelation function outside the data interval with a prediction error filter, and deriving the spectrum from this extended autocorrelation function. Tests on synthetic data showed that the shapes of spectra, and possibly the amplitudes as well, are quite satisfactory.

For high signal-to-noise ratio the spectra estimated in this way are in general agreement with those calculated by the conventional Fourier transform method, but show less ambiguity in their corner frequency, low-frequency asymptote, and high-frequency dependence on frequency. At low signal-to-noise ratio, Fourier methods cannot estimate these parameters at all, while the maximum entropy method yields clear-cut solutions in many cases.

In order to investigate the utility of the method as applied to the discrimination problem, P-wave maximum entropy spectra were calculated for 28 earthquakes and presumed explosions.

To determine the internal consistency of the data, and to find if the data fit the model, corner frequencies calculated by energy considerations were compared with those measured directly from spectra. The agreement was quite satisfactory.

Corner frequencies measured directly from spectra were plotted against magnitude for the whole data sample. There was a general trend for events with larger magnitudes to have lower corner frequencies, but the scatter in the data was so great as to prevent any conclusions concerning a frequency-magnitude relationship. There was very little separation between earthquakes and presumed explosions using this criterion. Consequently, we conclude that corner frequency, by itself, has very little discriminatory power.

A spectral magnitude, whose definition was motivated by spectral magnitudes calculated for local events, was found for the earthquake sample. It was a function of the zero-frequency spectral amplitude, the corner frequency, the epicentral distance, and one constant which was adjusted to minimize the variance between the spectral and network magnitudes. The network and spectral magnitudes found in this way were linearly related with a slope of nearly one. Then spectral magnitudes were found for the presumed explosions, using the relationship derived for earthquakes. These magnitudes were significantly higher than the corresponding network magnitudes, reflecting the higher stress associated with explosions. A discriminant based on this magnitude difference would have separated all earthquakes from explosions, and would have misclassified only one explosion.

The success of this single-valued discriminant led to the search for a more powerful test using two parameters. A discriminant combining deviations of the corner frequency from the value obtained from a regression of corner frequency on magnitude with magnitude difference gave an improved capability, but the data sample was still too small to draw reliable conclusions. The results suggest that measures of source dimension and stress have discriminating power and that further research on this topic is justified.

Some problems remain with maximum entropy spectra, however. In some situations additive random noise, coda, roundoff errors, and inherent limitations of the algorithm result in spectral power estimates less than zero at some frequencies. This is the most serious problem with the maximum entropy spectrum at this time.

In view of the improved spectra derived for events with low signal-to-noise ratio, and the more clear-cut measurements available from spectra with high signal-to-noise ratio as compared with conventional techniques, we recommend that more work on this subject be carried out. In particular the maximum entropy spectral estimation technique should be developed

so that it can be applied to events where it now finds negative power. The improved technique should be tested on artificial data of known characteristics in order to find the accuracy with which corner frequencies and levels are estimated.

This technique should then be applied to a broader data base comprising both teleseismic and regional events, and the discriminant based on spectral magnitude presented here should be further investigated. It is also possible that other more effective discriminants may be found in the course of such an investigation.

C. Technical Report No. 4 (Memorandum): Basic Seismic Analysis Of Regional Events Observed At NORSAR

The nature of discrimination at short distances can be quite different than that for teleseismic distances, because of the differences between regional and teleseismic magnitudes and because of the great variety of phases available at regional distances. This report considers some of the problems in regional event discrimination. All measurements were made using short-period data recorded at NORSAR.

First the observed P-wave travel times, as determined from the Preliminary Determination of Epicenters (PDE) locations were compared to those predicted by Herrin's (1968) travel-time curves. A great deal of scatter was found about the predicted times, caused by poor locations by NORSAR and in some cases by PDE, and by deviations of the local structure from that inferred by Herrin.

Next NORSAR single instrument m_b estimates were compared to the reported PDE measurements or to NORSAR beamed m_b's. The scatter in these data was too great to make any conclusions as to the applicability of the standard distance factors to events from these distances. However, it

was found that NORSAR single instrument m_b's were larger than those determined from the NORSAR beams by about 0.8 magnitude units due to high beamforming losses. Those determined by NOAA-PDE were larger than the single instrument NORSAR m_b's by about 0.3 magnitude units, due to the bias introduced when magnitudes are averaged over a few detecting stations. This bias prevented the determination of any relation between teleseismic and regional magnitudes in this study.

Finally, the utility of phase energy ratios as discriminants was investigated. The short-period seismogram was divided into three broad time frames containing compressional wave energy, shear wave energy, and surface wave energy, in that order. The total power in each time window was found and the ratios between them computed. There was separation using P/S ratios between presumed explosions and earthquakes but there were too few presumed explosions to state any conclusions with confidence. P/S ratios for earthquakes having epicenters determined by PDE were more consistent than for those located by NORSAR. However, there were only 5 such values which are certainly not enough for a good statistical sample. The presumed explosions from Novaya Zemlya have about the same P/S ratios. However, there were insufficient earthquake data to make any statements concerning the degree of separation between source types at this distance.

SECTION VI
SYSTEM ENGINEERING STUDIES

Under this task, an interactive graphics system was developed for the PDP-15 computer at the SDAC. The overall purpose of this Interactive Seismic Processing System (ISPS) is to provide an interactive graphics capability for the purpose of detecting and analyzing seismic waveforms. The system is primarily designed to operate in a potential surveillance mode, with emphasis on efficient processing of a large number of events.

A. Computer Program Product Specification: Documentation of the Interactive Seismic Processing System

The capabilities of the ISPS include:

- On-line display of seismic waveforms, with analyst option to select time windows, scaling and simultaneous display of different traces.
- Analyst selection of signal processing functions such as band-pass filtering, linear chirp filtering or crosscorrelation with a reference waveform.
- Interactive measurement of event parameters such as M_s, RMS noise and AR-AL discriminants (Brune, et al., 1963).

The software package is designed to handle any type of long- or short-period signal data that are input in a system compatible format. In particular, interfaces have been implemented to process data from the VLPE and SRO networks, and the ALPA, LASA, and NORSAR LP arrays.

This documentation presents a functional description of the software package. The objective of the package, the operating system environment and the hardware configuration is defined and the overall data flow is presented. The documentation status and procedures to update the documentation are also defined.

The documentation describes in detail the individual processing models of the ISPS system. For each program the purpose is stated, a detailed flow chart is given, and the methods and algorithms are discussed along with timing formats and possible program restrictions. For each of the main-line programs a comprehensive list of program variables and constants is included.

The documentation concludes with a discussion of operating considerations. Procedures for updating and linking the interactive system are detailed and examples are given of how to execute various system modules.

Appendices describe in detail the format of input magnetic tapes that are acceptable to the data base generation program of the ISPS system; the formats of disk files used by the ISPS system; and sample proglem output listings and plots, with explanations attached as to the command sequence leading to these output data.

B. Technical Report No. 9 (Memorandum): Expected Performance of Real-Time Interactive System

This report summarizes operator experience with the complex cepstrum and spectral analysis package implemented on the PDP-15 computer. The spectral analysis package performs all analyses ordinarily performed in batch mode by Texas Instruments Incorporated, requiring from 5 to 8 minutes to process a standard 4096 second data segment. All steps in the processing are initiated by the operator. This time requirement could be cut to about

2 1/2 minutes by automating the system to the point where the operator merely quality-checks the system's measurements. Under these circumstances the operator could reliably function for only about 2 hours, however, due to the monotonous nature of the work.

The complex cepstrum utilizes very little of the computer's time, because the operator is required to make a careful visual inspection of all its output. Its advantage over batch processing lies in the fact that the operator can quickly change input parameters and see the result of those changes. However, an experienced analyst will not require this feature, and would need no more than the interactive capability of the system, without its visual display.

SECTION VII
REFERENCES

Barnard, T. E., and L. J. O'Brien, 1974, An Evaluation of Adaptive-Beamforming Techniques Applied to Recorded Seismic Data. Technical Report No. 8, Texas Instruments Report No. ALEX(01)-TR-74-08, Contract Number F08606-74-C-0033, Texas Instruments Incorporated, Dallas, Texas.

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Lambert, D. G., A. I. Tolstoy, and E. S. Becker, 1974, Seismic Detection and Discrimination Capabilities of the Very Long Period Experiment. Texas Instruments Report No. ALEX(01)-TR-74-07, Contract Number F08606-74-C-0033, Texas Instruments Incorporated, Dallas, Texas.

Ringdal, F., and R. L. Whitelaw, 1973, Final Evaluation of the Norwegian Short-Period Array; Special Report No. 11, ALEX(01)-STR-73-11, Texas Instruments Incorporated, Dallas, Texas.

APPENDIX A

LIST OF REPORTS FROM CONTRACT F08606-75-C-0029

A. QUARTERLY REPORT

1. Quarterly Report No. 1, covering the period 1 December 1974 to 31 March 1975, Texas Instruments Report Number ALEX(01)-QR-75-01, 31 March 1975.

B. TECHNICAL REPORTS

1. Maximum Likelihood Estimation of Seismic Event Magnitude From Network Data, by Frode Ringdal, Texas Instruments Report Number ALEX(01)-TR-75-01, 27 March 1975.

2. Adaptive Beamforming Detection Performance on Korean Short-Period Interfering Events, by Wen-Wu Shen, Texas Instruments Report Number ALEX(01)-TR-75-02, 7 May 1975.

3. Time-Domain Wiener Adaptive Beamforming with Distributed Signal Models, by Thomas E. Barnard, Texas Instruments Report Number ALEX(01)-TR-75-03, 16 June 1975.

4. Basic Seismic Analysis of Regional Events Observed At NORSAR, by David G. Lambert, and Ervin S. Becker, Texas Instruments Report Number ALEX(01)-TR-75-04, (Memorandum), 2 July 1975.

5. Preliminary Evaluation of the Korean Seismological Research Station Short-Period Array, by Sidney R. Prahl, Wen-Wu Shen, and Richard L. Whitelaw, Texas Instruments Report Number ALEX(01)-TR-75-05, 29 July 1975.

6. A Study of Adaptive Beamforming Detection Performance on ALPA Interfering Events, by Wen-Wu Shen, Texas Instruments Report Number ALEX(01)-TR-75-06, 28 July 1975.

7. An Automatic Seismic Detection Algorithm, by David G. Black, and Stephen S. Lane, Texas Instruments Report Number ALEX(01)-TR-75-07, 31 July 1975.

8. Corner Frequency Study, by Robert L. Sax, Texas Instruments Report Number ALEX(01)-TR-75-08, (Memorandum), 31 July 1975.

9. Expected Performance of Real-Time Interactive System, Texas Instruments Report Number ALEX(01)-TR-75-09, (Memorandum), 31 July 1975.

C. DOCUMENTATION

1. Documentation of the Interactive Seismic Processing System (ISPS), by Frode Ringdal, Jeffrey S. Shaub, and David G. Black, Texas Instruments Report Number ALEX(01)-SD-75-01, 10 June 1975.

D. FINAL REPORT

1. Final Report, VELA Network Evaluation and Automatic Processing Research, by Stephen S. Lane and Staff, Texas Instruments Report Number ALEX(01)-FR-75-01, 31 July 1975.